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SULPHIDE STRESS CRACKING TESTS ON GAS TRANSMISSION LINEPIPE

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PHYSICAL METALLURGY RESEARCH LABORATORIES

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SULPHIDE STRESS CRACKING TESTS ON GAS TRANSMISSION
LINE PIPE

by

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ABSTRACT

The results of sulphide stress cracking measurements on nine gas transmission line pipes are presented to record progress and serve as a basis for discussion.

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INTRODUCTION

It has been observed since about 1950 that steels under tensile stress can fail by cracking upon exposure to wet H_2S environments. Such failures are often referred to as sulphide stress cracking (SSC), and the phenomenon has been extensively reviewed (1,2). The National Association of Corrosion Engineers (NACE) has developed standard test method TM-01-77 for evaluating the resistance of metals to SSC at ambient temperatures (3). Basically, this test consists of the exposure of metal specimens under tensile loading to an acidified chloride solution that is saturated with H_2S . Typical results obtained using the methods described in TM-01-77 are presented in references 4 and 5.

The susceptibility to SSC of a number of gas transmission line pipes has been investigated at the Physical Metallurgy Research Laboratories (PMRL) of CANMET, Energy, Mines and Resources Canada, as part of Pipeline Project 420602 since April 1980 (6).

The present report is of a phenomenological nature, and details the results obtained in standard SSC tests with a minimum of interpretation. It will be supplemented by one or more future reports embodying the results of metallographic and fractographic examinations of the specimens tested which will aid in defining the mechanism(s) of SSC.

EXPERIMENTAL

MATERIALS

Nine samples of commercial gas transmission line pipe, procured by PMRL for this and other research, have been tested for susceptibility to SSC.

Table 1 provides a general description of the pipes. Mechanical and representative impact properties are given in Table 2 and chemical compositions in Table 3. Hardness values were determined at PMRL and appear in Table 4.

Pipes AB and Z are examples of commercial practice in Canada during 1975-76 and were manufactured to Foothills Pipeline Limited Specification P100 (1975) for the Alaska Highway Pipeline Project. A comprehensive metallurgical evaluation of these pipes has been published (7). Pipes AE, AG and CC were manufactured in Canada during 1979-80 for Arctic service and embody improvements in technology compared with AB and Z.

Pipes CA, CB and CD were also manufactured in Canada during 1979-80 and are typical products of this period. Pipe CA was designed for natural gas transmission in the U.S.A., while CB was designed for similar service in Canada. CD was manufactured for gas and liquid transportation pipelines not requiring specific notch toughness properties.

Pipe CE differs from the others in that it was manufactured in 1981 in Japan specifically for sour gas service.

Examination of metallographic sections of the mill welds of each of the as-received pipes showed no sign of weld cold cracking or other internal damage. This confirmed the results of similar examinations by J.T. McGrath and co-workers at PMRL on pipes AB, AE, AG and Z.

METHODS

The test methods used were those described in NACE standard test method TM-01-77 (3). This method employs tensile specimens with a gauge length of 25.4 mm and a diam of 6.4 mm. Because of its smaller wall thickness, sub-size specimens 4.36 mm in diam had to be made from pipe CD. Two types of specimens were prepared as follows:

1. Parent specimens, with their lengths transverse to the plate rolling direction, taken from the pipe near the mill weld;
2. Weld specimens, with their lengths transverse to the direction of the mill weld, and having the weld in the middle of the gauge length.

In both types of specimen, the gauge length was excluded as much as possible from any straightening operations performed on the plate during specimen fabrication.

Mechanical properties were determined at PMRL for two parent and two weld specimens of each pipe. Reproducibility was good and the average values obtained are presented in Table 5.

In SSC tests each degreased specimen was first weighed on an analytical balance. The specimen was then subjected to a selected tensile stress, after which it was immersed in an H_2S - saturated solution (0.5% acetic acid, 5% sodium chloride; pH of 2.8 prior to H_2S saturation). This test solution is often referred to as the "NACE Solution". Stress was applied to the specimens by means of a "Cortest" proving ring, as shown in Fig. 1. The time to failure was measured by means of a timer which stopped when the specimen failed. The test was terminated if a specimen did not fail after 30 days.

Specimens from each pipe were tested over a range of applied tensile stresses, such that the maximum "threshold stress" at which specimens endured 30 days without failure could be determined. The binary search procedure shown in Fig. 2 was used, with some minor modifications, for the majority of the pipe specimens (8). The first specimen of each alloy is tested at an applied stress equal to half the specimen's ultimate tensile stress. As Fig. 2 shows, the stress applied at each succeeding step in the procedure is predicated on whether the specimen has failed, or survived for 30 days.

After a specimen had failed (or after 720 h immersion without failure) the H_2S was turned off and the test solution equilibrated with nitrogen. The "final solution pH" was determined after the specimen was removed from its containing cell. The specimen was then partially cleaned in tap water, and subsequently completely descaled by immersion in inhibited acid. It was then re-weighed and in diam re-measured. By measuring the area stained by corrosion, the area in contact with the solution during the test was calculated for use in determining the mass-loss corrosion rate.

RESULTS

SSC TESTS

SSC failures were of a brittle character, with specimens usually separating into two pieces showing little or no necking at fracture surfaces. The results of the SSC tests, in terms of time-to-failure vs applied stress, are presented for both parent and weld specimens in Tables 6 to 14. Ratios of the applied stress to the yield stress (AS/YS) are also given, the yield stresses being those obtained on SSC test specimens (Table 5).

Figures 3-6 show the ratio AS/YS vs time to failure on semi-logarithmic plots for both parent and weld specimens. At higher stresses, such curves are usually linear and show increasing times to failure with decreasing applied stress. At some lower stress there is an elbow in the curve at or near the threshold value at which specimens survive for 30 days without failure. More tests would be necessary to better define the curves in some instances.

The most important parameter obtained from the SSC data is the threshold stress, which can be considered as an index of resistance to SSC. This stress can be expressed as such, or as a ratio to yield stress, viz: threshold stress/yield stress. Threshold stresses from Tables 6-14 are grouped for

both parent and weld metal in Table 15, along with the corresponding ratios of threshold stress/yield stress.

In Fig. 7, threshold stress is plotted against yield stress for both parent and weld specimens, while Fig. 8 shows threshold stress/yield strength ratios plotted against specimen yield strength. In both figures, the scatter band was drawn to enclose data points from seven parent specimens.

CORROSION RATES

A number of measurements indicative of corrosion behaviour were performed in connection with the SSC tests. Tables 16 to 24 provide corrosion penetrations calculated from mass loss, and also list the duration of immersion of specimens in H_2S -saturated NACE solution. Corrosion rates in $\mu m/a$ are calculated for each specimen from these data. Final solution pH values, determined in the nitrogen-saturated solution after completion of the tests, are also given. Specimens are listed in the same order as in Tables 6 to 14.

(i) Diametral Measurements

In addition to measuring the amount of corrosion penetration by mass loss, decreases in the diameter of the specimen gauge length were also determined. Corrosion penetrations given by the two methods for parent and weld specimens that had not failed after 720 h on test are plotted in Fig. 9. A linear relationship was obtained with considerable scatter, particularly at the lower values. The line intercepted the x-axis at about 23 μm , indicating that the specimen diameters were essentially unchanged by light pitting attack yielding mass-loss corrosion penetrations of this order. Although, corrosion was assessed in this research by the more sensitive mass-loss method, diametral measurements are rapid and easy, and can be used for monitoring purposes, particularly when the corrosion rate is significant.

(ii) Comparison of Pipes

As shown in Tables 16 to 24, the immersion of specimens for 720 h led to corrosion rates ranging from 250 to 1870 $\mu m/a$. This range was unexpectedly high. Furthermore, considerable variation was shown by different specimens of the same pipe - e.g., for parent AG and Z. Examination of the data failed to show any relationship between this erratic behaviour and the level of applied load during testing, or the alloy yield and tensile strengths. Possible

sources of error included slow changes of temperature in the range 20-30°C, corrosion contributions by the emerging fracture surfaces, and corrosion during the periods of arbitrary length in nitrogenated solutions at the termination of tests. Clearly, SSC tests as normally performed are not designed to produce accurate corrosion rates.

Differences in corrosion behaviour among the pipes, therefore, could not be established definitively. However, it appeared from the 720 h immersions that CA corroded at the lowest rates (250-340 $\mu\text{m/a}$), while the highest corrosion rates were shown by AB(750-1470 $\mu\text{m/a}$) and Z(620-1870 $\mu\text{m/a}$).

(iii) Kinetics of Corrosion

Scatter and the relatively small number of data points made it difficult to determine corrosion kinetics from corrosion penetration vs time of immersion plots. However, four of the best defined curves are shown in Fig. 10.

As would be expected, clean specimens corroded initially at a rapid rate, most frequently in the range 2000-3000 $\mu\text{m/a}$ for immersions less than 50 h (Fig. 11). There is then a decrease in rate, presumably because of the formation of a protective film. Thus, corrosion rates based on immersions of 720 h are considerably lower than those of less than 50 h and are most frequently in the range 750-1000 $\mu\text{m/a}$ (Fig. 12).

(iv) Solution Depletion

Corrosion processes cause an overall depletion of hydrogen ions during SSC tests. The extent of the depletion was indicated by the routine pH measurements, performed in nitrogenated solutions after completion of each test. As shown in Tables 16 to 24, there was an increase in pH in every case relative to the initial value of 2.8 prior to H_2S saturation.

Figure 13 shows the relationship between final solution pH and corrosion penetration for all SSC tests performed. For corrosion penetrations up to about 100 μm , and perhaps higher, pH values were found to lie in a scatter band about 1.0 pH units wide. However, there was a trend towards higher pH values as corrosion increased.

The variability of pH in the final solution was greater than expected, and appeared to be due in part to differing behaviour among the steels. Thus, for a given amount of corrosion, specimens from pipes CA and Z are associated with the largest increases in pH, while those from CE and CD are as-

sociated with the smallest. Figure 14 shows this. For clarity, the data for other pipes were not plotted in Fig. 14, but fall within the limits shown.

DISCUSSION

SSC TESTS

NACE Standard Test TM-01-77 was found to give consistent results in terms of establishing threshold stresses for resistance to SSC for each pipe. Use of the binary search method minimized the number of specimens needed to establish threshold stresses.

Parent specimens behaved more consistently than weld specimens. Seven of the nine pipes showed threshold stresses that increased with increasing yield strength over the YS range 368-646 MPa. The other two pipes - AG and Z - showed much higher threshold stresses than the rest and were evidently more resistant to SSC (Fig. 7).

Weld specimens generally showed lower threshold stresses than parent specimens of the same yield strength, with pipes AE, CB, CD, CE and Z being particularly susceptible. Unexpectedly, weld specimens from pipes AB and CC showed higher thresholds than the corresponding parent specimens (Fig. 7).

CORROSION RATES

Corrosion measurements on the SSC specimens were subject to a number of shortcomings inherent in the SSC test procedures and provided only approximate results. But the tests were sufficiently consistent to show high initial corrosion rates (most frequently 2000-3000 $\mu\text{m/a}$) which decreased after the first 50 h, presumably because of the development of a protective film. Based on 720 h immersions, corrosion rates were most frequently in the range 750-1000 $\mu\text{m/a}$. Some of the mass loss data suggest that, after filming had led to a reduction in corrosion rate, there was a subsequent increase in rate, perhaps, as the film began to spall. Certainly, quantities of dark flakes of non-adherent corrosion film were often generated during the tests. But there were insufficient reliable data to establish this mechanism beyond doubt.

The pH values of test solutions were observed to increase generally with corrosion penetration of the specimen from the initial value of about 2.8 to as high as 4.6. In a current (1982) revision of NACE Standard TM-01-77, Task Group T-1F-9 proposes that all tests showing final solution pH values

greater than 4.5 should be invalidated. Figure 13 shows only one such case, for the specimen of pipe Z that showed the maximum corrosion penetration observed in this research.

An increase in pH values would be expected during SSC tests primarily because of removal of hydrogen ions in the reaction:



The differences in pH shift occurring for different pipes indicate that other ions in addition to Fe^{2+} have an influence on the reaction because they go into solution, and hydrolyse or precipitate out. The final solution pH may depend in a complex manner upon the chemical composition of the corroding specimen. Alloys such as Z, with both a high corrosion rate and a strong tendency to cause increased solution pH, may sometimes "fail" the final solution pH requirement of the NACE SSC test.

SUMMARY

The most important results are summarized below:

1. Consistent behaviour was obtained in NACE Standard TM-01-77 SSC tests on parent and weld specimens from nine gas transmission linepipes, including Grades 290-483.
2. Parent specimens showed increased threshold stresses for resistance to SSC with increasing yield strength over the range 368-646 MPa. But pipes AG and Z showed higher thresholds than other pipes of similar strength.
3. Weld specimens showed more erratic behaviour and generally lower threshold stresses than corresponding parent specimens. But weld specimens from AB and CC showed higher thresholds than parent specimens from these pipes.
4. Specimens corroded at high initial rates (most frequently 2000-3000 $\mu\text{m/a}$) but the rate usually decreased to 750-1000 $\mu\text{m/a}$ for immersions of 720 h. Erratic results made comparisons between pipes difficult but AB and Z appeared to corrode at the highest rates, and CA at the lowest.
5. pH values of depleted solutions, measured after tests, always increased from the initial value of 2.8 to a final value in the range 2.9-4.6. Different pipe steels affected final solution pH to differing extents, with corroding specimens from CA and Z generating the largest increases in pH values and those from CD and CE the smallest.

FUTURE WORK

SEM examination of SSC specimen fracture surfaces and metallographic sectioning of specimen gauge lengths are planned, to aid in defining cracking mechanisms. Comparisons will also be made between SSC and the cracks produced in stepwise cracking (SWC) tests, which are being performed concurrently on the same nine pipes.

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Table 1. Line pipes used in research.

Pipe	Size (diam x wall thickness)	Grade	Notes
AB	1067 x 13.7 mm	483 (X70)	semi-killed, ingot-cast, controlled-rolled, spiral sub-arc welded
AE	1219 x 13.7 mm	483 (X70)	fully-killed, ingot-cast, controlled-rolled, spiral sub-arc welded
AG	914 x 13.7 mm	483 (X70)	fully-killed, ingot-cast, controlled-rolled, spiral sub-arc welded
CA	610 x 13.5 mm	359 (X52)	fully-killed, ingot-cast, controlled-rolled, longi- tudinal sub-arc welded
CB	762 x 11.7 mm	448 (X65)	fully-killed, ingot-cast, controlled-rolled, longi- tudinal sub-arc welded
CC	1219 x 13.7 mm	483 (X70)	fully-killed, ingot-cast, controlled-rolled, spiral sub-arc welded
CD	508 x 9.53 mm	290 (X42)	semi-killed, ingot-cast, hot rolled, longitudinal sub-arc welded
CE	864 x 15.9 mm	359 (X52)	fully-killed, continuous cast, controlled-rolled, longitudinal sub-arc welded
Z	1067 x 13.7 mm	483 (X70)	fully-killed, ingot-cast, controlled-rolled, spiral sub-arc welded

Table 2. Mechanical and impact properties provided by manufacturers.

Code	Yield strength MPa	Ultimate tensile strength MPa	Elong. %	Impact properties
AB body weld	516 -	639 696	36 -	DWTT @ -18°C 6504 J 100% shear
AE body weld	574 684	762 796	33 20	DWTT @ -4°C 4813 J 100% shear Charpy @ -4°C 125 J 99% shear
AG body	524	645	36	DWTT @ -20°C 5934 J 87% shear Charpy @ -20°C 214 J 100% shear
CA body weld	417 -	514 552	38 -	DWTT @ 0°C 2298 J 98% shear Charpy @ 0°C (2/3 size): 26 J 94% shear
CB body weld	470 -	576 599	38 -	DWTT @ -5°C 1085 J 50% shear Charpy @ -5°C (2/3 size): 31 J 98% shear
CC body	493	635	40	DWTT @ -4°C 5627 J 100% shear Charpy @ -4°C 117 J 94% shear

Table 2 (cont'd)

CD	body	397	516	31	-
	weld	-	544	-	
CE	body	383	471	46	DWTT @ -20°C
	weld	410	504	31	100% shear
					Charpy @ -20°C
					298 J
Z	body	503	633	39	DWTT @ -18°C
	weld	-	749	-	5694 J
					90% shear
					Charpy @ -18°C
					115 J
					96% shear

Table 3. Analyses of line pipes provided by manufacturers, wt%.

Element	AB	AE	AG	CA	CB	CC	CD	CE	Z
C	0.06	0.08	0.08	0.13	0.12	0.060	0.22	0.068	0.049
Mn	1.80	1.98	1.70	1.17	1.48	1.76	0.85	0.86	1.94
P	0.009	0.011	0.014	0.005	0.011	0.004	0.004	0.006	0.007
S	0.017	0.005	0.004	0.016	0.010	0.006	0.028	0.001	0.011
Si	0.02	0.29	0.15	0.27	0.27	0.25	0.06	0.256	0.28
Nb	0.058	0.045	0.072	0.015	0.038	-	-	0.020	0.060
Sn	0.02	0.005	0.015	-	0.002	-	-	-	-
Cu	0.22	0.053	0.23	-	0.029	0.028	-	-	-
Ni	0.11	0.033	0.20	-	0.012	0.009	-	0.37	-
Cr	0.04	0.097	0.09	-	0.057	0.044	-	-	-
Mo	0.27	0.24	0.21	-	0.007	0.212	-	-	0.489
V	-	0.05	-	-	0.040	0.035	-	-	-
Al	-	0.017 ⁽¹⁾	-	-	0.024 ⁽¹⁾	0.034 ⁽¹⁾	-	0.024 ⁽²⁾	-
Ca	-	-	-	-	-	-	-	0.0037	-
O	-	-	-	-	-	-	-	0.0025	-
N	-	-	-	-	-	-	-	0.0038	-
C/E	0.44 ⁽³⁾	0.47	0.45 ⁽³⁾	0.33	0.37	0.40	0.36	0.24	0.37

(1) acid-soluble

(2) total

(3) calculated by: $C/E = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$

Table 4. Rockwell macrohardness of pipes used in SSC measurements.

Pipe	Parent (1)		Weld heat-affected zone		Weld fusion zone	
	Av	No. of	Av	No. of	Av	No. of
	hardness R _B	determinations	hardness R _B	determinations	hardness R _B	determinations
AB	93.2	21	93	3	97	3
AE	96.3	21	98 ⁽²⁾	3	97.5	3
AG	95.2	21	95	3	97	3
CA	85.1	21	86	3	90.5	3
CB	90.9	21	91.5	3	94.5	3
CC	91.5	21	94	3	97	3
CD	85.8	21	83.5	3	83	3
CE	78.9	21	82	3	93	3
Z	92.4	21	95	3	98 ⁽²⁾	4

(1) Determined at locations adjacent to the weld, and 90° and 180° around the pipe circumference from the weld.

(2) This is also equal to HRC 20.5.

Table 5. Mechanical properties of pipes as determined on SSC specimens.

Pipe	Grade	Type	0.2% offset	Ultimate tensile strength, MPa	Elongation, %	Reduction in area, %
			Yield strength, MPa			
AB	483	parent	518	643	18.5	43.5
		weld	582	660	16	39.5
AE	483	parent	646	744	21.5	64.5
		weld	642	710	17.5	57
AG	483	parent	597	678	25	72.5
		weld	563	661	20	62
CA	359	parent	418	531	26	51
		weld	432	537	21.5	51
CB	448	parent	494	600	28.5	56
		weld	510	615	18	58.5
CC	483	parent	526	618	25	60
		weld	591	662	20	64.5
CD	290	parent	416	548	25.5	52.5
		weld	453	547	16.5	53
CE	359	parent	368	463	37.5	74
		weld	374	496	21.5	73.5
Z	483	parent	538	673	26	69.5
		weld	614	691	16.5	56

Table 6. SSC behaviour in H₂S-saturated NACE solution of pipe AB.

Specimen type	Yield strength (YS), MPa	Specimen No.	Applied stress (AS), MPa	Ratio: AS/YS	Time to failure, h
parent	518	AB-2	483	0.932	14.7
		AB-3	459	0.886	23.4
		AB-4	434	0.838	25.4
		AB-5	410	0.792	23.0
		AB-6	410	0.792	33.8
		AB-7	386	0.745	84.8
		AB-8	367	0.708	45.1
		AB-1	348	0.672	720NF*
		AB-9	338	0.653	720NF
weld	582	ABW-2	459	0.789	19.4
		ABW-3	434	0.746	23.1
		ABW-4	410	0.704	720NF
		ABW-1	386	0.663	720NF

*NF - no failure

Table 7. SSC behaviour in H₂S-saturated NACE solution of pipe AE.

Specimen type	Yield strength (YS), MPa	Specimen No.	Applied stress (AS), MPa	Ratio: AS/YS	Time to failure, h
parent	646	AE-2	571	0.884	4.6
		AE-3	476	0.736	13.7
		AE-5	453	0.700	8.6
		AE-4	429	0.663	720NF*
		AE-1	381	0.589	720NF
weld	642	AEW-1	381	0.594	117.7
		AEW-3	333	0.519	33.4
		AEW-4	309	0.482	720NF
		AEW-2	285	0.445	720NF

*NF - no failure

Table 8. SSC behaviour in H₂S-saturated NACE solution of pipe AG.

Specimen type	Yield strength (YS), MPa	Specimen No.	Applied stress (AS), MPa	Ratio: AS/YS	Time to failure, h
parent	597	AG-5	565	0.946	448
		AG-4	545	0.912	720NF*
		AG-3	524	0.878	720NF
		AG-2	484	0.811	720NF
		AG-1	323	0.541	720NF
weld	563	AGW-2	484	0.859	20.9
		AGW-3	403	0.716	19.7
		AGW-4	363	0.645	11.5
		AGW-5	343	0.608	720NF
		AGW-1	323	0.573	720NF

*NF - no failure

Table 9. SSC behaviour in H₂S-saturated NACE solution of pipe CA.

Specimen type	Yield strength (YS), MPa	Specimen No.	Applied stress (AS), MPa	Ratio: AS/YS	Time to failure, h
parent	418	CA-1	323	0.772	~35.3 ⁽¹⁾
		CA-3	287	0.686	54.1
		CA-5	269	0.643	720NF ⁽²⁾
		CA-4	251	0.600	720NF
weld	432	CAW-5	323	0.747	33
		CAW-2	323	0.747	~44.8 ⁽³⁾
		CAW-1	287	0.664	94
		CAW-4	269	0.623	720NF
		CAW-3	251	0.581	720NF

(1) Timer malfunction, failure between 27.5 and 43 h

(2) NF = no failure

(3) Timer malfunction, failure between 22.5 and 67.1 h

Table 10. SSC behaviour in H₂S-saturated NACE solution of pipe CB.

Specimen type	Yield strength (YS), MPa	Specimen No.	Applied stress (AS), MPa	Ratio: AS/YS	Time to failure, h
parent	494	CB-1	403	0.816	~35.5 ⁽¹⁾
		CB-2	359	0.726	39.4
		CB-4	348	0.705	168.2
		CB-3	336	0.680	720NF ⁽²⁾
weld	510	CBW-1	403	0.792	12.6
		CBW-2	359	0.704	21.6
		CBW-3	314	0.616	72.9
		CBW-4	291	0.572	~325 ⁽³⁾
		CBW-6	279	0.548	97
		CBW-5	269	0.528	720NF

(1) Timer malfunction; failure between 27 and 43.5 h

(2) NF = No failure

(3) Timer malfunction; failure between 317 and 332 h

Table 11. SSC behaviour in H₂S-saturated NACE solution of pipe CC.

Specimen type	Yield strength (YS), MPa	Specimen No.	Applied stress (AS), MPa	Ratio: AS/YS	Time to failure, h
parent	526	CC-2	476	0.907	7.4
		CC-3	397	0.755	24.2
		CC-4	357	0.680	211
		CC-5	337	0.642	41.1
		CC-1	317	0.604	720NF*
weld	591	CCW-2	476	0.806	11.1
		CCW-5	456	0.772	20.3
		CCW-4	436	0.738	720NF
		CCW-3	397	0.671	720NF
		CCW-1	317	0.536	720NF

*NF - no failure

Table 12. SSC behaviour in H₂S-saturated NACE solution of pipe CD.

Specimen type	Yield strength (YS), MPa	Specimen No.	Applied stress (AS), MPa	Ratio: AS/YS	Time to failure, h
parent	416	CD-2	387	0.930	14.3
		CD-3	322	0.775	23.6
		CD-4	290	0.698	24
		CD-5	274	0.658	21.5 ⁽¹⁾
		CD-1	258	0.620	720NF ⁽²⁾
weld	453	CDW-2	387	0.854	8.1
		CDW-3	322	0.711	14.8
		CDW-4	290	0.641	7.8
		CDW-5	274	0.605	27.6 ⁽³⁾
		CDW-1	258	0.570	720NF

(1) Power interruption; failure between 20 and 23 h

(2) NF = No failure

(3) Power interruption; failure between 26 and 29.2 h

Table 13. SSC behaviour in H₂S-saturated NACE solution of pipe CE.

Specimen type	Yield strength (YS), MPa	Specimen No.	Applied stress (AS), MPa	Ratio: AS/YS	Time to failure, h
parent	368	CE-2	353	0.960	12.2
		CE-3	294	0.800	18.5
		CE-4	265	0.720	34.1
		CE-5	250	0.680	232.5
		CE-1	235	0.640	720NF*
weld	374	CEW-2	353	0.943	11.7
		CEW-1	235	0.629	~56.8**
		CEW-5	221	0.590	54.5
		CEW-4	206	0.550	720NF
		CEW-3	177	0.472	720NF

*NF - no failure

**Power interruption; failure between 49 and 64.5 h

Table 14. SSC behaviour in H₂S-saturated NACE solution of pipe Z.

Specimen type	Yield strength (YS), MPa	Specimen No.	Applied stress (AS), MPa	Ratio: AS/YS	Time to failure, h
parent	538	Z-6	507	0.942	12.8
		Z-4	483	0.897	194.8
		Z-5	459	0.852	720NF*
		Z-3	434	0.807	720NF
		Z-2	386	0.717	720NF
		Z-1	348	0.646	720NF
weld	614	ZW-5	386	0.629	56.8
		ZW-1	348	0.566	311
		ZW-2	314	0.511	28.7
		ZW-4	314	0.511	720NF
		ZW-3	290	0.472	720NF

*NF - no failure

Table 15. Threshold (maximum) stresses at which specimens survived 30 days in NACE solution without failure.

Pipe	Threshold stress, MPa		Ratio: <u>Threshold stress</u> <u>Yield stress</u>	
	Parent	Weld	Parent	Weld
AB	348	410	0.672	0.704
AE	429	309	0.663	0.482
AG	545	343	0.912	0.608
CA	269	269	0.643	0.623
CB	336	269	0.680	0.528
CC	317	436	0.604	0.738
CD	258	258	0.620	0.570
CE	235	206	0.640	0.550
Z	459	314	0.852	0.511

Table 16. Corrosion behaviour in SSC tests in H₂S-saturated NACE solution on pipe AB.

Specimen type	Specimen No.	Period of immersion, h	Corrosion penetration, μm	Corrosion rate, $\mu\text{m/a}$	Final solution pH
parent	AB-2	16.5	11.6	6160	3.3
	AB-3	25.5	6.2	2130	3.3
	AB-4	40.5	12.1	2620	3.3
	AB-5	43	6.5	1330	3.2
	AB-6	43	6.8	1390	3.1
	AB-7	139	21.5	1360	3.1
	AB-8	46	10.7	2040	3.1
	AB-1	720	107.6	1310	4.0
	AB-9	720	61.4	750	3.7
weld	ABW-2	25.5	6.1	2100	3.3
	ABW-3	23.5	5.6	2090	3.1
	ABE-4	720	120.8	1470	4.3
	ABW-1	720	93.2	1130	4.1

Table 17. Corrosion behaviour in SSC tests in H₂S-saturated NACE solution on pipe AE.

Specimen type	Specimen No.	Period of immersion, h	Corrosion penetration, μm	Corrosion rate, $\mu\text{m/a}$	Final solution pH
parent	AE-2	6	4.9	7160	3.0
	AE-3	16.75	7.6	3980	3.1
	AE-5	16.25	10.7	5770	3.2
	AE-4	720	46.9	570	3.6
	AE-1	720	48	580	3.8
weld	AEW-1	136	20.7	1330	3.3
	AEW-3	49	17.6	3150	3.5
	AEW-4	720	29.4	360	3.6
	AEW-2	720	82	1000	3.8

Table 18. Corrosion behaviour in SSC tests in H₂S-saturated NACE solution on pipe AG.

Specimen type	Specimen No.	Period of immersion, h	Corrosion penetration, μm	Corrosion rate, $\mu\text{m/a}$	Final solution pH
parent	AG-5	498	45	790	3.4
	AG-4	720	72.9	890	4.2
	AG-3	720	65.7	800	4.0
	AG-2	720	33.2	400	3.6
	AG-1	720	98.5	1200	3.8
weld	AGW-2	22	5.9	2350	3.2
	AGW-3	21	9.8	4090	3.3
	AGW-4	21	9.1	3800	3.2
	AGW-5	720	78.1	950	3.8
	AGW-1	721.3	79.1	960	3.8

Table 19. Corrosion behaviour in SSC tests in H₂S-saturated NACE solution on pipe CA.

Specimen type	Specimen No.	Period of immersion, h	Corrosion penetration, μm	Corrosion rate, $\mu\text{m/a}$	Final solution pH
parent	CA-1	43	9.3	1900	3.6
	CA-3	168	10.4	540	3.8
	CA-5	720	24.1	290	3.6
	CA-4	720	20.4	250	3.9
weld	CAW-5	40	12.3	2700	3.5
	CAW-2	67.1	7.1	930	3.9
	CAW-1	167.25	6.3	330	3.7
	CAW-4	720	28.1	340	3.8
	CAW-3	720	23.4	280	4.1

Table 20. Corrosion behaviour in SSC tests in H₂S-saturated NACE solution on pipe CB.

Specimen type	Specimen No.	Period of immersion, h	Corrosion penetration, μm	Corrosion rate, $\mu\text{m/a}$	Final solution pH
parent	CB-1	43.5	7.7	1550	3.6
	CB-2	115.5	14.1	1070	3.6
	CB-4	185	12.0	570	3.3
	CB-3	720	42.6	520	3.9
weld	CBW-1	19	6.7	3090	3.4
	CBW-2	23.5	5.8	2160	3.2
	CBW-3	115.5	9.6	730	3.3
	CBW-4	332	22.1	580	3.6
	CBW-6	97	22.7	2050	3.5
	CBW-5	720	62.0	750	4.0

Table 21. Corrosion behaviour in SSC tests in H₂S-saturated NACE solution on pipe CC.

Specimen type	Specimen No.	Period of immersion, h	Corrosion penetration, μm	Corrosion rate, $\mu\text{m/a}$	Final solution pH
parent	CC-2	18.5	5.2	2460	3.0
	CC-3	40	18.7	4100	3.7
	CC-4	216	30.9	1250	3.6
	CC-5	48.5	19.5	3520	3.5
	CC-1	720	68.9	840	3.9
weld	CCW-2	18	9.8	4770	3.3
	CCW-5	23.9	7.7	2820	3.1
	CCW-4	720	105.5	1280	3.6
	CCW-3	720	72.5	880	3.7
	CCW-2	720	92.1	1120	3.7

Table 22. Corrosion behaviour in SSC tests in H₂S-saturated NACE solution on pipe CD.

Specimen type	Specimen No.	Period of immersion, h	Corrosion penetration, μm	Corrosion rate, $\mu\text{m/a}$	Final solution pH
parent	CD-2	20	8.2	3590	3.3
	CD-3	24	19.4	7090	3.3
	CD-4	24.8	9.4	3320	3.0
	CD-5	24	8.0	2920	3.3
	CD-1	720	36.9	450	3.6
weld	CDW-2	16.5	5.0	2660	3.2
	CDW-3	16	5.1	2790	3.0
	CDW-4	18	7.4	3600	3.0
	CDW-5	29.2	12.3	3680	3.0
	CDW-1	720	133.8	1630	4.0

Table 23. Corrosion behaviour in SSC tests in H₂S-saturated NACE solution on pipe CE.

Specimen type	Specimen No.	Period of immersion, h	Corrosion penetration, μm	Corrosion rate, $\mu\text{m/a}$	Final solution pH
parent	CE-2	21	8.1	3380	3.1
	CE-3	18.75	10.3	4820	3.0
	CE-4	40	7.6	1670	3.0
	CE-5	233	25.0	940	3.4
	CE-1	720	43.4	530	3.6
weld	CEW-2	20	6.5	2850	2.9
	CEW-1	64.5	11.7	1590	3.4
	CEW-5	65.5	15.9	2130	3.4
	CEW-4	720	64.8	790	3.6
	CEW-3	720	69.6	850	3.6

Table 24. Corrosion behaviour in SSC tests in H₂S-saturated NACE solution on pipe Z.

Specimen type	Specimen No.	Period of immersion, h	Corrosion penetration, μm	Corrosion rate, $\mu\text{m/a}$	Final solution pH
parent	Z-6	18	8.6	4190	3.2
	Z-4	261.6	27.6	920	4.3
	Z-5	720	51.3	620	3.9
	Z-3	720	153.7	1870	4.6
	Z-2	720	75.7	920	4.2
	Z-1	720	96.6	1180	4.1
weld	ZW-5	92	10.8	1030	3.8
	ZW-1	312	13.0	370	4.0
	ZW-2	41	8.8	1880	3.5
	ZW-4	720	105.6	1290	4.1
	ZW-3	720	87.3	1060	4.5

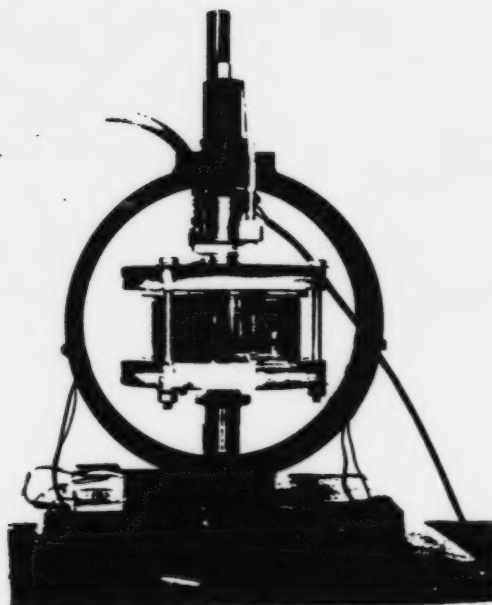


Fig. 1. SSC specimen under test in "Cortest" proving ring.
(neg 4490)

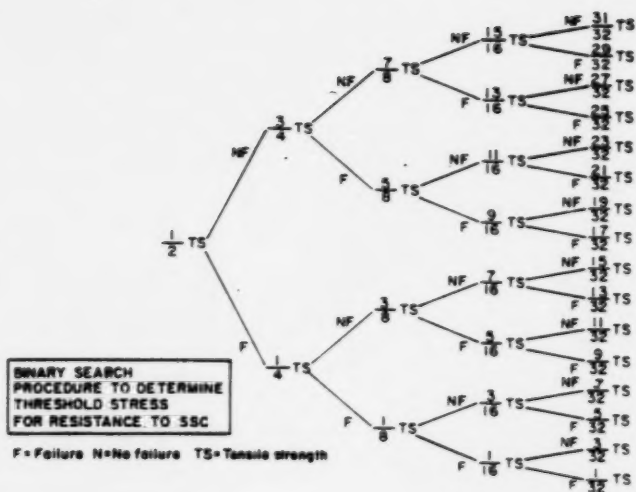


Fig. 2. Binary search procedure for determining threshold stress for resistance to SSC. After ref (8). (neg 7231)

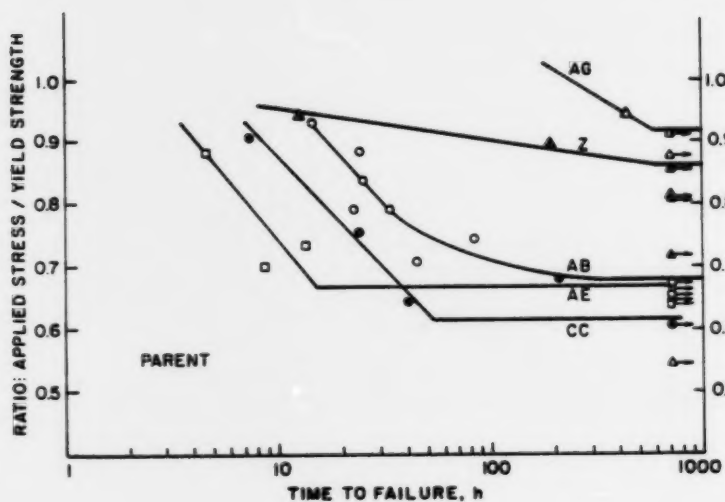


Fig. 3. Applied stress/yield strength ratio vs time to failure for parent specimens of AB, AE, AG, CC and Z. (neg 7230).

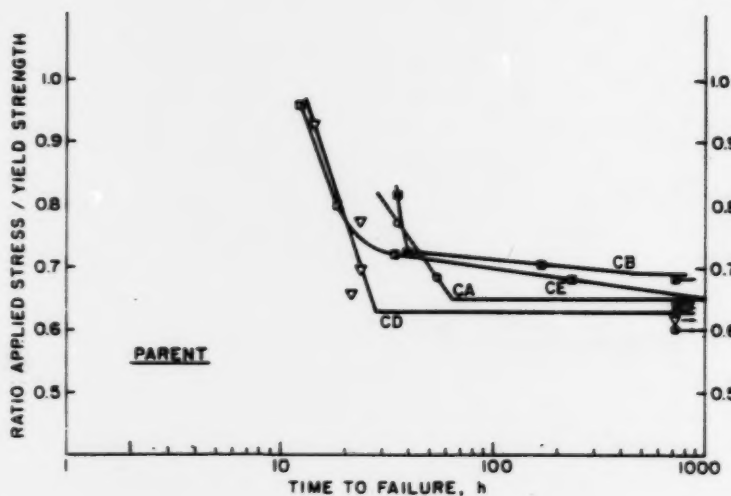


Fig. 4. Applied stress/yield strength ratio vs time to failure for parent specimens of CA, CB, CD and CE. (neg 7229)

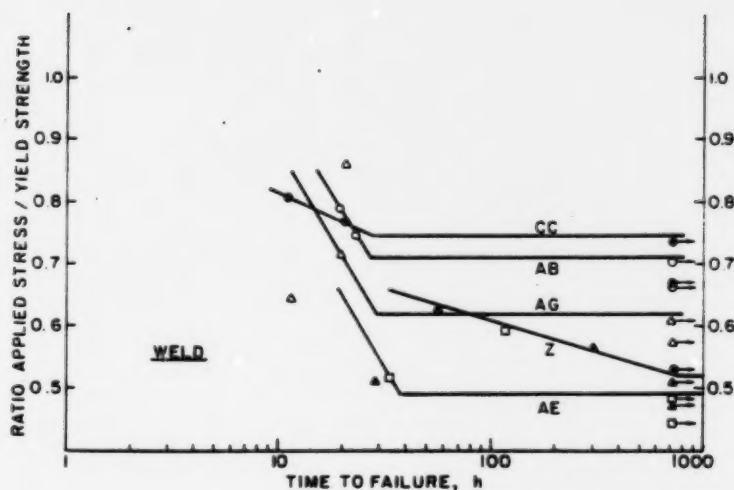


Fig. 5. Applied stress/yield strength ratio vs time to failure for weld specimens of AB, AE, AG, CC and Z. (neg 7228)

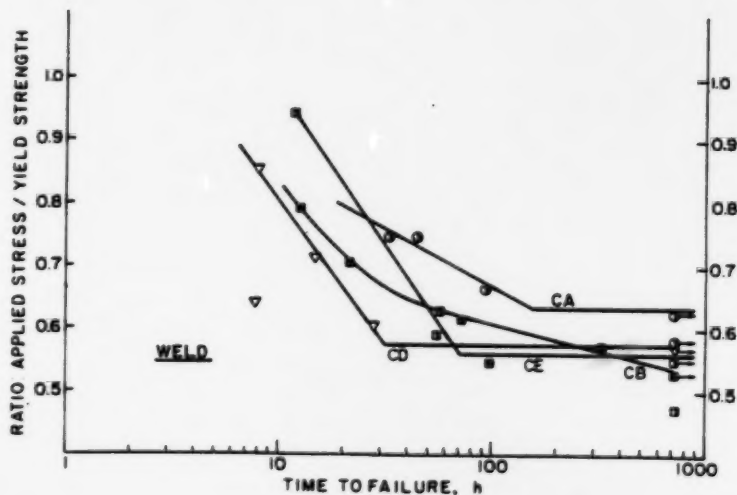


Fig. 6. Applied stress/yield strength ratio vs time to failure for weld specimens of CA, CB, CD, and CE. (neg 7227)

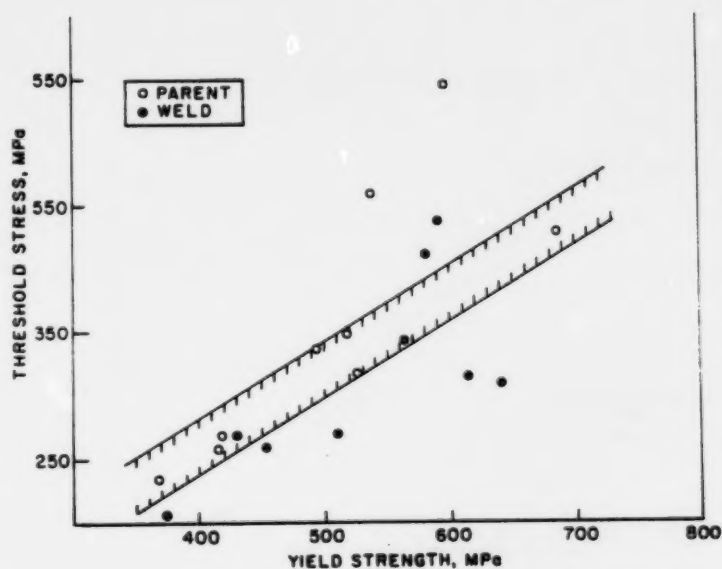


Fig. 7. Threshold strength vs yield strength for parent and weld specimens. (neg 7420)

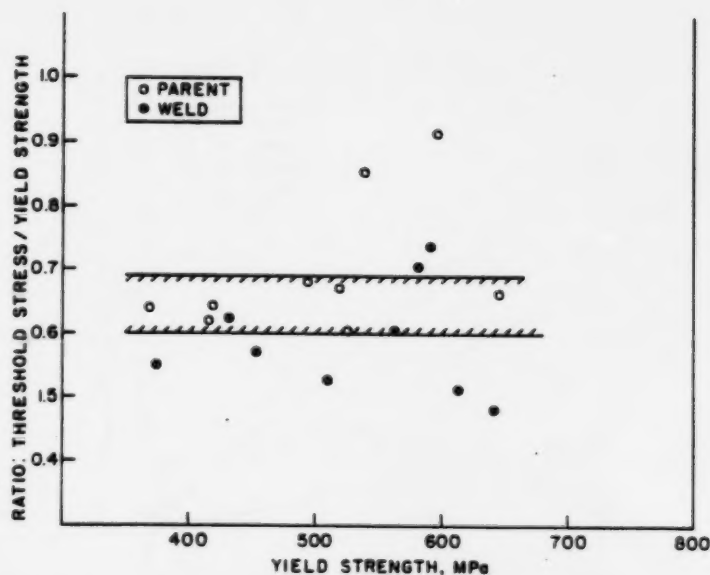


Fig. 8. Threshold stress/yield strength ratio vs yield strength for parent and weld specimens. (neg 7226)

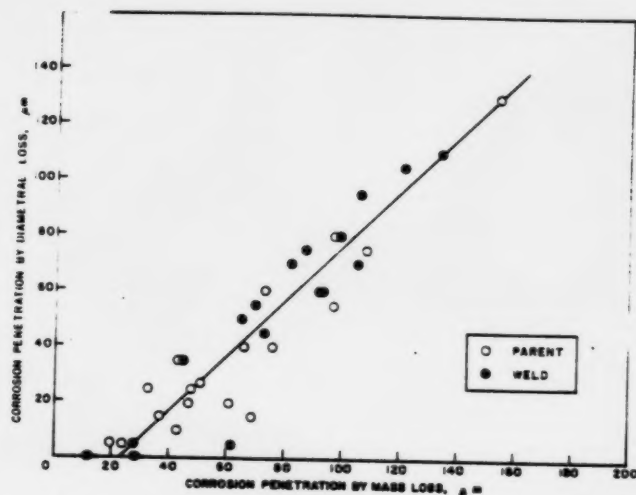


Fig. 9. Comparison of mass and diametral loss measurements for specimens which had not failed after 720 h on test. (neg 7449)

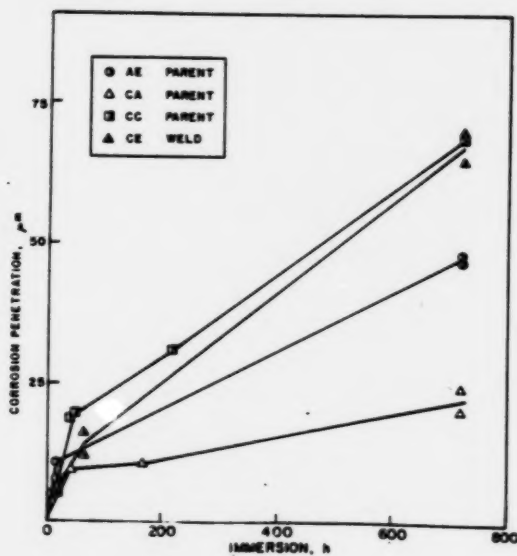


Fig. 10. Corrosion penetration vs immersion time plots for several pipes. (neg 7448)

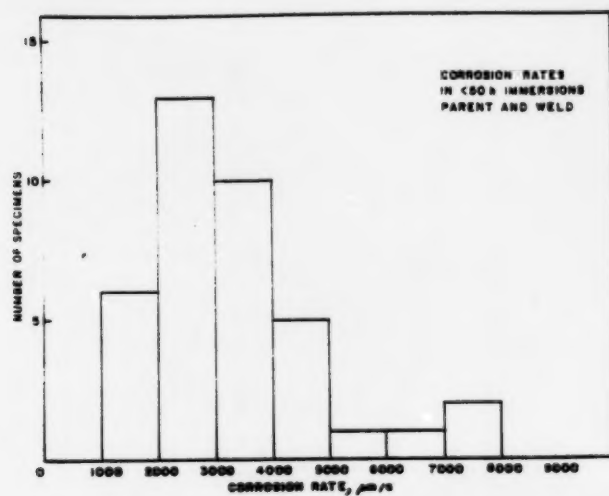


Fig. 11. Frequency distribution of corrosion rates for specimens immersed less than 50 h. (neg 7453)

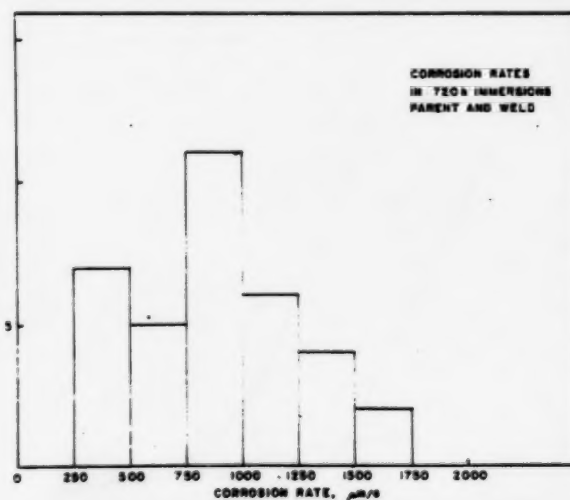


Fig. 12. Frequency distribution of corrosion rates for specimens immersed 720 h. (neg 7451)

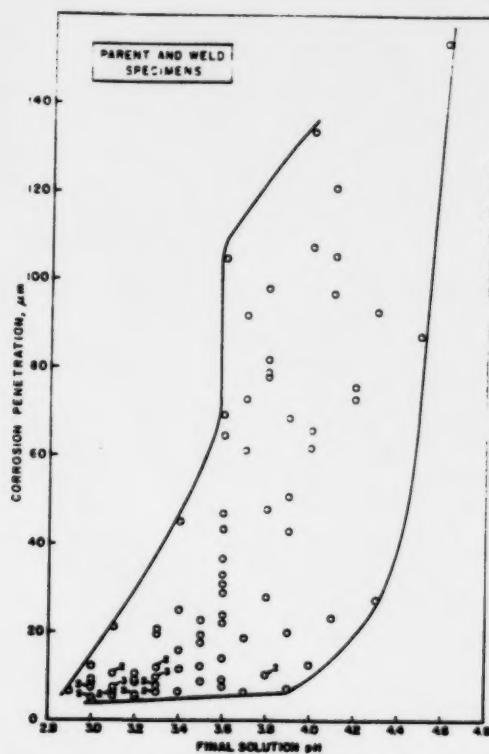


Fig. 13. Corrosion penetration vs final solution pH for all test specimens. (neg 7452)

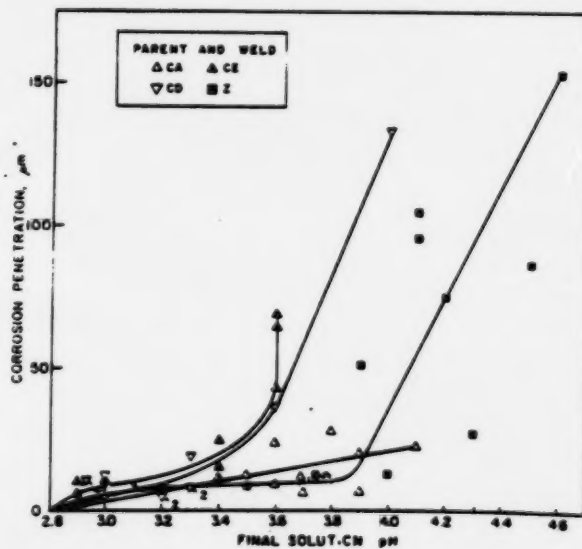


Fig. 14. Corrosion penetration vs final solution pH showing differences between pipes. (neg 7450)

